AFRL-IF-RS-TR-2001-285
In-House Technical Report
December 2001

AN ANALYSIS OF AN ULTRA-HIGH SPEED CONTENT-ADDRESSABLE DATABASE RETRIEVAL SYSTEM

Peter J. Costianes

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AFRL-IF-RS-TR-2001-285 has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 2001	IN HOUSE FINAL REPORT, 25 JUL 00 - 25 JUN 01

4. TITLE AND SUBTITLE
AN ANALYSIS OF AN ULTRA-HIGH SPEED CONTENT-ADDRESSABLE DATABASE RETRIEVAL SYSTEM

5. FUNDING NUMBERS
IN HOUSE
PR - 459E
PE - 62702f
TA - H0
WU - D1

6. AUTHOR(S)
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ROME NY 13441-4114

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-IF-RS-TR-2001-285

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFRL/IFED
32 Brooks Road
Rome, NY 13441-4114

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-IF-RS-TR-2001-285

11. SUPPLEMENTARY NOTES
AIR FORCE RESEARCH LABORATORY PROJECT ENGINEER: PETER J. COSTIANES, AFRL/IFED/315-330-4030

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This work presents a model for assessing the performance of a paradigm and its implementation first proposed by Chou, Detofsky, and Louri entitled "Multiwavelength Optical Content-Addressable Parallel Processor (MW-OCAPP) and its implementation as a high speed optical chip. The paradigm uses polarization states to represent binary query words and EO modulators to represent database words to perform what is essentially XOR operations. The model was created using Matlab M-files consisting of custom and built-in functions. Polarization is represented by the Jones Vectors. All polarizations are considered to be linear. Since the model only addresses the temporal characteristics of the EO modulators, transmission losses due to possible waveguide losses and insertion losses between interfacing subsystems are not considered. The grating subsystem is assumed to have a constant loss across all wavelengths which is arbitrarily set at 90% loss. The final photodector array has a linear response.

14. SUBJECT TERMS
Database retrieval system, polarization, EO modulators

15. NUMBER OF PAGES
32

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclas	Unclas	Unclas	U

Table of Contents

List of Figures

Chapter 1: Introduction

Over the past 20 years, much basic research has been conducted on the use of optical techniques to process, store, and retrieve information. Recent efforts in advanced development are concentrating mainly on how to write and read large amounts of data without any consideration for the data content. Some researchers have predicted that within the next five years it is expected that working optical systems will be developed to accomplish this task. Once these systems are commercialized and improved upon, the need will become more demanding to selectively query and retrieve information based also on its content in these optical memories. Most of the techniques proposed for associative-content based retrieval use optical correlation, optical neural networks, and opto-electronic/integrated optics implementations[1]. Approaches using opto-electronics/integrated circuits appear to be the most promising technologies to compete with the highly successful electronic approaches.

This Technical Report presents a model for assessing the performance of a paradigm and its implementation first proposed by Chou, Detofsky, and Louri entitled Muliwavelength Optical Content-Addressable Parallel Processor (MW-OCAPP) [2] and its implementation as a high speed optical integrated chip in a paper entitled Equivalency Processing Parallel Phontonic Integrated Circuit (EP^{3}IC)[3]. The paradigm uses polarization states to represent binary query words and EO modulators to represent database words to perform what is essentially XOR operations. The

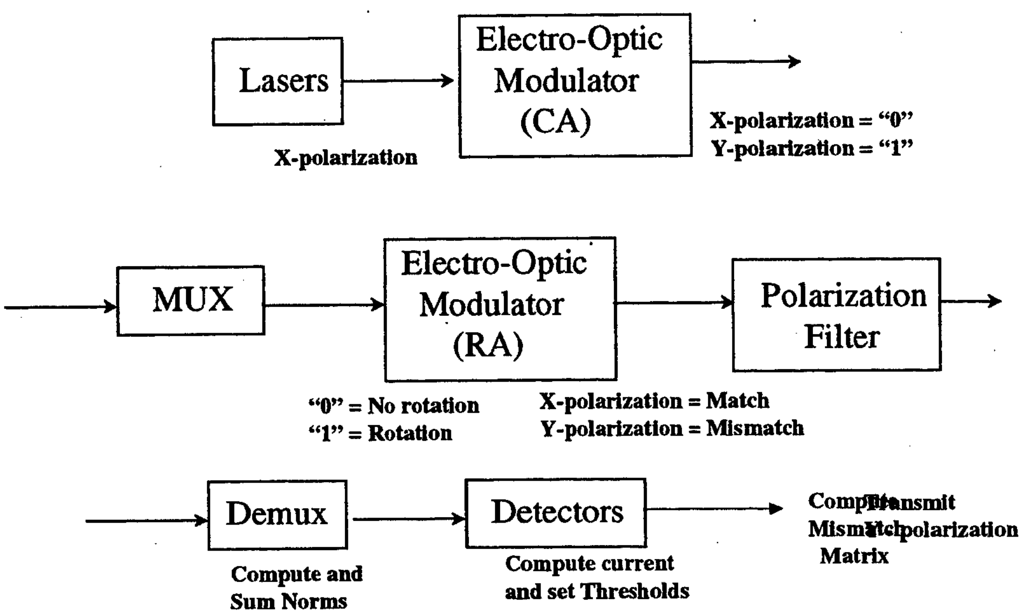

Figure 1. System block diagram

proposed implementation uses an 32x32 array of multiwavelength lasers to input the query – each row (word) being of single wavelength with 32 bits per row with a 8x32 array of polarization modulators to input the database words for comparison. Estimated performance showed a throughput rate of 82 Tbits/sec. Of all approaches researched, this one showed the most promise for providing a significant increase in capability over present electronic state-of-

the-art technology and any other optical approaches in development.(The paradigm is represented here as a system model block diagram shown in figure 1.

The paradigm was successfully demonstrated using large-scale optics. As a result of this successful demonstration, implementation using micro-optics and, even, an integrated optical chip were investigated. The unique feature of this approach lies in the use of two EO modulators to represent binary query words and binary database words, respectively. Initial efforts did not consider the performance of the concept in terms of the temporal characteristics of the EO modulators. The model presented here focuses mainly on the temporal performance of the EO modulators and how they affect system performance with all other elements in the system being assumed ideal.

Chapter 2: System Model

The block diagram for the system model is shown in figure 1. The model was created completely using MATLAB M-files consisting of custom and built in Matlab functions. Polarization is represented by using a Jones Vector[4]. All polarizations are considered to be linear. Since the model only addresses the temporal characteristics of the EO modulators, transmission losses to due to possible waveguide transmission losses and insertion losses between interfacing subsystems are not considered. The grating subsystem is assumed to have a constant loss across all wavelengths which is arbitrarily set at 90%. The final photodetector array has a current output which has a linear response to input light over wavelengths specified in the model.

2.1 Laser Subsystem

The laser subsystem is modeled using an array of 8x8 ideal lasers with fixed x-polarization output and a total power per pulse of 1 watt and 8 different wavelengths. Each wavelength corresponds to a single row in the laser array as specified in the MW-OCAPP (see figure 2). The temporal characteristics are modeled using 5 different standard pulses which are

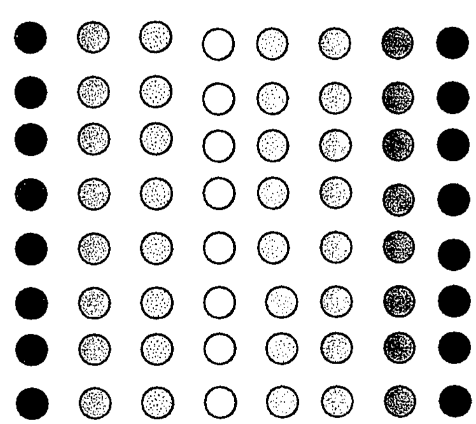

Figure 2. Laser Array

the positive lobes of sinewaves at 5 different frequencies (see figure 3). The five frequencies were selected to be multiples of 2, i.e, f, 2f, 4f, 8f, 16f, giving periods of T, T/2, T/4, T/8, T/16. Since the positive pulse of each sinewave was used, the pulse durations are ½ the periods. Each pulse is sampled 1000 times. These 5 standard pulses are also used in defining the temporal characteristics of the EO modulators. As we will see later, the actual pulse frequencies are not important in defining the performance of the system based on the two modulators. The actual characteristic measure will be based on the pulse duration ratio between the laser pulse and pulse

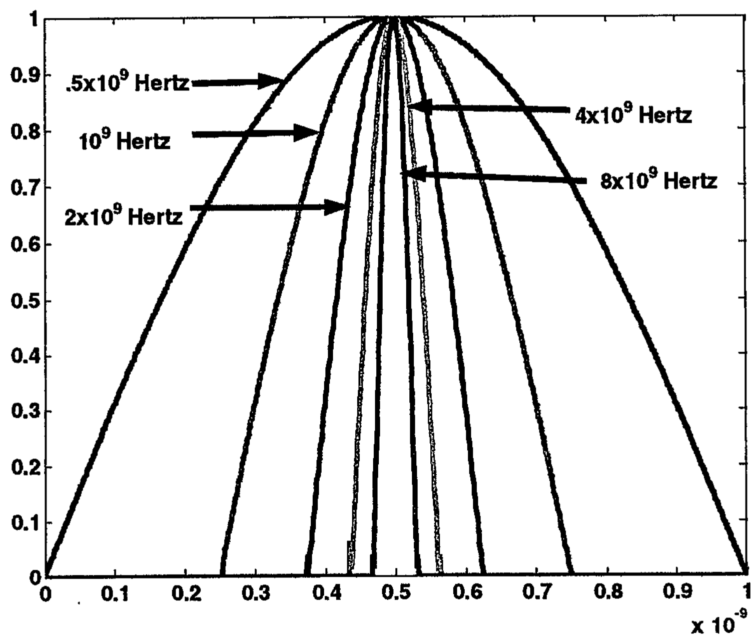

Figure 3. 5 Standard Sine Pulses Used for temporal model of Lasers & Modulators

driving the polarization rotation of the EO modulators.

2.2 Comparand Array (CA)

The CA is where the query word is input into the system. It is an EO modulator which rotates the polarization represented by a Jones Vector input from the laser array (see figure 4). The EO modulator is an 8x8 array of cells. Each cell is illuminated with x-polarized light by a single laser in the 8x8 laser array. Each row (8 bit word) of the CA is illuminated by a single row of the laser array with a single wavelength output, 8 different wavelengths 8 different words in the CA. Any bits in the CA that are a "0" will allow the light to pass unaltered in polarization. Bits in the CA that are a "1" will rotate the input laser light resulting in an output of y-polarized light.

Of course, this rotation is not instantaneous due to the finite temporal response of the EO modulator. Here we use one of the 5 standard pulses mentioned above. In fact, without loss of generality, the widest of pulse is used. For example, if we also use the widest standard pulse for the laser, the leading edge of the laser pulse (for a "1") will barely get rotated. The maximum rotation will be effected at the center of the laser pulse which, in this case, corresponds to the center of the pulse driving the EO modulator with no rotation again at the trailing edge of the

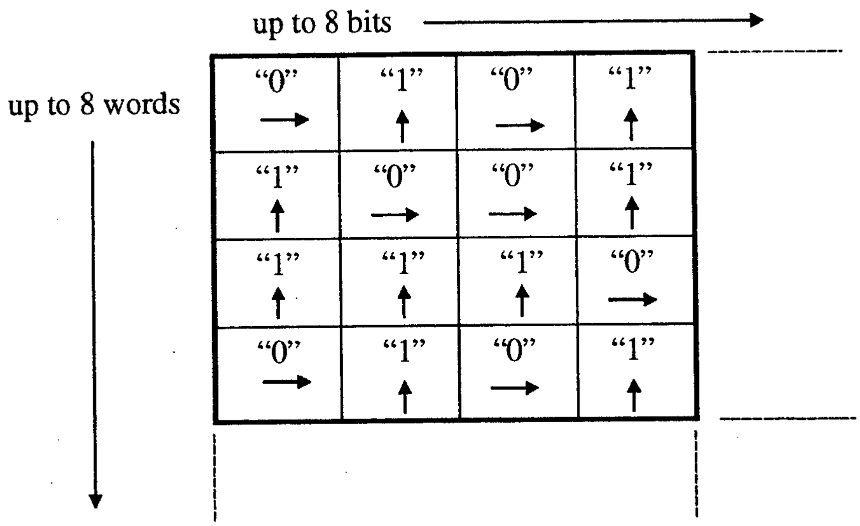

Figure 4. Comparand Array for first 4 bits
and first 4 words (EO Modulator)

laser pulse. It is quite obvious that we always wish the laser pulse durations to be equal to or less than the duration of the pulse driving the rotation in the EO modulator. In fact, it is appropriate to fix the pulse duration for both the CA and RA EO modulators for the maximum duration standard pulse while just varying the laser pulse durations to determine the effect of the finite rotation times on the total power through the system. As we shall see later, the total power through the system is a measure of the match between the words in the CA and RA. Also, the synchronization is assumed such that the maximum of the laser pulses always and perfectly match with the maximum rotation of the EO modulators. The maximum rotation angle θ is modeled as a gaussian random variable which varies from bit cell to bit cell in the CA.

In summary, the output of the CA will be a pulse whose polarization at maximum power will be x-polarized to represent a "0" and y-polarized to represent a "1". This will occur only at time sample t =500. However, since the maximum power angle of polarization is now a random variable, a "0" will be represented by a beam with "almost" x-polarization and a "1" will be represented by a beam with "almost" y-polarization. The Jones Rotation matrix is given by:

$$T = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

This matrix operates on the Jones Vector $[\, x \quad y \,]^T$ where T denotes a transpose. This rotation is carried on for each time sample for t =1 to t = 1000.

2.2 MUX

This is a simple multiplexing step where all the light coming from the first bit of each word in the CA is focused on the first bit of each of the 8 words in the RA and likewise for all bits up to 8. One might say we are matching the first bits between the CA and RA to see if there is a match.

2.3 Relational Array (RA)

up to 8 bits

up to 8 words

"0" **no rotation**	"1" **rotation**	"0" **no rotation**	"1" **rotation**
"1" **rotation**	"0" **no rotation**	"0" **no rotation**	"1" **rotation**
"0" **no rotation**	"0" **no rotation**	"1" **rotation**	"1" **rotation**
"0" **no rotation**	"1" **rotation**	"1" **rotation**	"0" **no rotation**

Figure 5. Relational Array (RA) for first 4 bits and first 4 words (EO Modulator)

The RA is where the database word is input into the system. It is an EO modulator which rotates the polarization represented by a Jones Vector input from the CA. The rotation in this case is accomplished according to the following rules for no randomness and a maximum rotation angle of 90^0 (see figure 5):

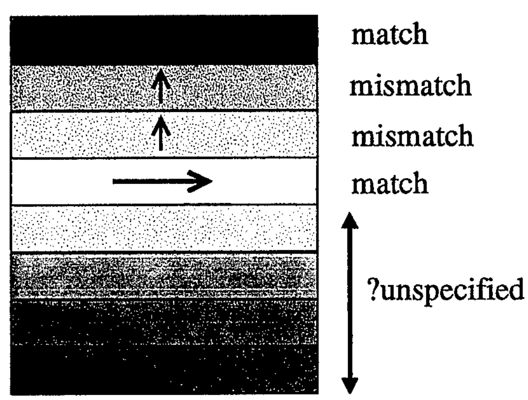

Figure 6. Multiplexed and matched output from RA single cell representing first bit of first word.

If CA = "0" and RA = "0" - no rotation - outputs a $[\,1 \quad 0\,]^T$
If CA = "1" and RA = "1" - rotation of 90^0 – outputs a $[\,1 \quad 0\,]^T$
If CA = "0" and RA = "1" - rotation of 90^0 – outputs a $[\,0 \quad 1\,]^T$
If CA = "1" and RA = "0" - no rotation - outputs a $[\,0 \quad 1\,]^T$

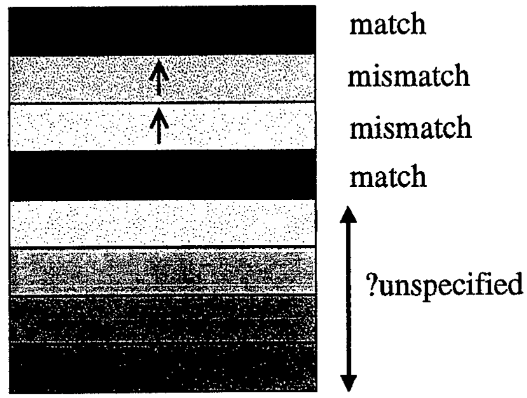

Figure 7. Light output from polarization filter. Black denotes no light.

The rotation matrix is the same one used in the CA. Again, the rotation is carried on for each time sample from t = 1 to t = 1000. The maximum rotation angle θ is modeled as a gaussian random variable which varies from bit cell to bit cell in the RA.

From the above four "If" statements it is obvious that if the bits in the CA and RA match, the light will come out x – polarized and if they mismatch the light will come out y-polarized. Figure 6 shows the resultant multiplexed output from the RA for all wavelengths and the polarizations for the first bits of the first four words of the RA matched with the first word first bit of the CA. The output from this cell is a superposition of 8 different wavelengths, each with a polarization determined by the rules above.

2.4 Polarization Filter

The polarization filter is selected for maximum transmission for y-polarized light. Each Jones Vector from the RA is passed through the filter. All light that was a result of a match is attenuated and all light that was a result of a mismatch is passed with maximum transmission. The polarization filter is given as:

$$T(\theta) = \begin{bmatrix} \cos 2\,\theta & \sin\theta\cos\theta \\ \sin\theta\cos\theta & \sin^2\theta \end{bmatrix}$$

The output from the polarization filter is given by the expression

$$PFout\,(i,j,k,m) = RAout\,(i,j,k,m)\;T(\theta)$$

Where i = 1:no. of rows in CA
j = 1:no. of rows in RA
k = 1: no.of bits per word (same for CA and RA)
m = 1:1000 time samples for each pulse
$\theta = 90^0$

PFout = Array of match/mismatch Jones Vectors output by filter
RAout = Array of match/mismatch Jones Vectors output from RA

The output from the filter is shown in figure 7. Where there was a match condition, there is no light transmitted. The attenuation for the last four colors is unspecified since, for economy, we did not choose to make bit assignments in this reduced example. Whether or not the last four colors were present in the output from this cell would depend on the bit assignments in these words in both the CA and RA.

2.5 DEMUX

The DEMUX or demultiplexing operation is accomplished by an optical grating which spatially separates the light back into its constituent wavelengths. Recall the original standard pulses used for the CA and RA. These pulses are sampled into 1000 time samples with sample 500 falling at the peak of the pulse. For example, PFout (1,1,1,1) is the output Jones Vector resulting from a match of the first bit of the CA with the first bit of the RA for the first words in the CA and RA at pulse sample t = 1. PFout(1,1,2,1) is the output Jones Vector resulting from a match of the second bit of the CA and the second bit of the RA for the first word of the CA and the first word of the RA at pulse sample t = 1, on up to the 8th bit. These 8 Jones Vectors are vector summed to get the resultant vector at time sample t = 1. Norms are then summed of all time samples from 1 to 1000 which represents the total optical optical power resulting from matching word 1 of the CA with word 1 of the RA. And so on for all other 63 word matches.

2.6 Detector Subsystem

The optical output consisting of an array of 8x8 norms (total power per match/mismatch) is focused on a detector array which converts it to a 8x8 array of current values. Each current

CA bit	RA bit	Resulting current in detector	
0	0	0	
1	1	0.0339	PW 0
0	1	0.0675	
1	0	0.0675	
0	0	0	
1	1	0.0132	PW 1
0	1	0.0752	
1	0	0.0752	

Etc. for other pulse widths

Figure 8. Computed relative currents

reflects the degree to which each pair of words in the CA and RA are matched. Since there are 8 bits per word there are 8 possible match mismatch conditions, i.e., no bits match, 1 bit match, 2 bit match, up to 8. This is a measure of the Hamming Distance between CA and RA word matches. To determine the amount of energy passed for each of the possible bit matches CA = 0/RA=0, CA=1/RA=1, CA=0/RA=1, and CA=1/RA=0, the model was run for a one bit CA and a one bit RA using these combinations. This produced the total optical power out for these possibilities. Since the power measurements are also a function of laser pulse duration, the same set of combinations was run for each of the standard pulses. PW0 denotes a laser pulse width equal to the pulse duration driving the rotation angle on the EO modulators, PW1 denotes a laser pulse width equal to ½ the pulse duration driving the EO modulators, and so on up to PW8 which is a pulse duration equal to 1/8 the pulse duration driving the EO modulators. Figure 8 shows computed relative currents for each of the four match/mismatch conditions and laser pulse durations of PW0 and PW1. Since all words are 8 bits long, the total power for each word match/mismatches will be a sum of these possible combinations.

2.7 Classification of Output/Computing the Mismatch Matrices

To determine the decision regions for measuring degree of mismatch (Hamming Distance), all possible 8 bit words were generated to create a training set. Using the results for single bit matches above, a range of current values were generated for each of the 256 (8 bits/word) word matches and clustered according to the number of bit mismatches. Decision boundaries were selected which became the threshold values between regions. This is shown in figure 9. Any unknown current output plotted along the y-axis resulting from a specific pair of word matches was assigned a classification of Hamming Distance plotted along the x-axis if it fell within that specific decision region. For example, in figure 9 the value y current falls within the decision boundary for 4 mismatches or a Hamming Distance of 4. The x's in the figure denote training data which originally established the regions as stated above.

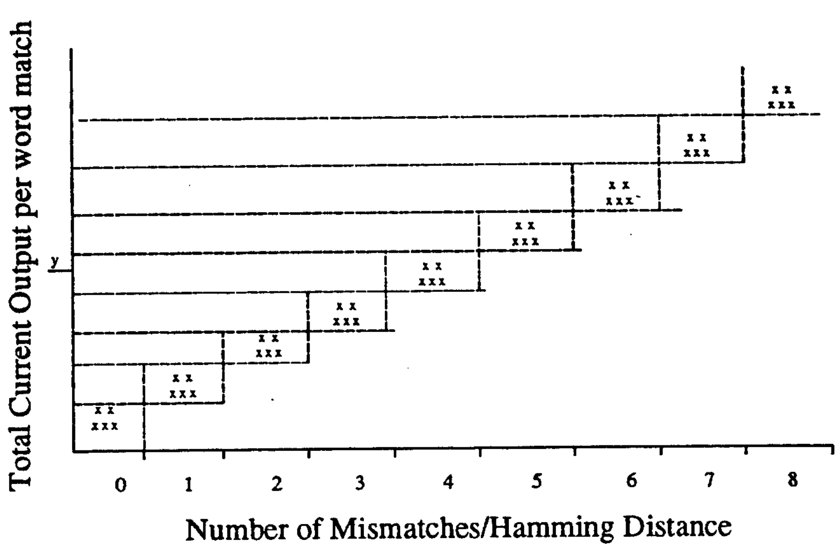

Figure 9. Decision regions for determining Hamming Distance

Figure 10 shows 4 matrices. The matrix at the upper left corner is 8 randomly selected words of 8 bits placed in the CA and RA. The CA and RA were loaded with the same set of 8 words. This was done in order to assure that there would be some words between the CA and RA that would match. If the CA and RA were both generated randomly, this would not have been the case and data collected for word matches would have been sparse. The Ideal Mismatch

Figure 10. CA/RA and mismatch matrices

k = row no. in CA/RA
l = column no. in CA/RA

k →, l ↓

1	0	1	0	1	1	0	0
1	0	1	1	1	1	0	0
1	1	0	1	0	0	1	0
0	0	0	1	0	0	0	1
0	1	0	0	1	1	0	1
1	0	1	0	1	1	1	0
0	0	0	1	0	1	0	1
0	1	1	1	0	1	1	1

Input CA and RA

i = row no. in CA
j = row no. in RA

i →, j ↓

0	1	6	6	4	1	5	6
1	0	5	5	5	2	4	5
6	5	0	4	6	5	5	4
6	5	4	0	4	7	1	4
4	5	6	4	0	5	3	4
1	2	5	7	5	0	6	5
5	4	5	1	3	6	0	3
6	5	4	4	4	5	3	0

Ideal mismatch matrix

0	1	0	1	0	1	0	1
1	1	0	0	0	1	0	1
0	0	0	1	0	0	0	1
1	0	1	0	1	1	1	0
0	0	0	1	0	0	0	1
1	1	0	1	0	1	0	1
0	0	0	1	0	0	0	1
1	1	1	0	1	1	1	2

Bit mismatch error between Ideal and Computed

0	2	6	5	4	2	5	7
2	1	5	5	5	3	4	6
6	5	0	3	6	5	5	5
5	5	3	0	3	6	0	4
4	5	6	3	0	5	3	5
2	3	5	6	5	1	6	6
5	4	5	0	3	6	0	4
7	6	5	4	5	6	4	2

Mismatch matrix computed by model

Matrix (upper right corner) was generated to represent perfect performance. Each i,j element in this matrix gives the number of bit matches between word i in the CA and word j in the RA. Since the CA and RA were identical, the diagonal elements (i = j) show zero mismatches. This same set of data in the CA/RA was then processed through the optical model resulting in the matrix in the lower right corner with some randomness imposed on the rotation angles in both the CA and RA. When this computed Mismatch Matrix is differenced element by element with the Ideal Mismatch Matrix, the resulting bit mismatch errors for each word pair comparisons is shown in the matrix in the lower left hand corner.

Chapter 3: Performance Results

To measure performance under varying laser pulse durations and statistical variations, a pulse duration ratio was defined as follows:

$$\text{Pulse Duration Ratio} \equiv \text{PDR} = \frac{\text{pulse duration of CA/RA polarization rotation pulse}}{\text{pulse duration of laser pulse}}$$

For the laser pulses used and keeping both the CA/RA pulses the same (longest of the 5 standard pulses), the PDR can take on the following values: 1,2,4,8,16.

The parameters driving the randomness of the maximum rotation angle in both the CA and RA were generated as follows:

data1	θmean = 89.50 deg,	θsigma = 0.15 deg
data2	θmean = 89.25 deg,	θsigma = 0.25 deg
data3	θmean = 88.50 deg,	θsigma = 0.50 deg
data4	θmean = 87.90 deg,	θsigma = 0.70 deg
data5	θmean = 87.00 deg,	θsigma = 1.00 deg
data6	θmean = 86.40 deg,	θsigma = 1.20 deg

Finally, the sum of all the elements of the matrix representing bit mismatch errors between the ideal and computed is plotted on the ordinate of figure 11 with the PDR on the absicssa. As shown in the figure, each set of data1-6 is plotted as a separate colored plot. For the ideal case of no randomness in the maximum rotation angle, the plot for a PDR of 1 is the coordinate (0,1). Of course any other larger PDR's will also give the result of zero error for the perfect EO modulators.

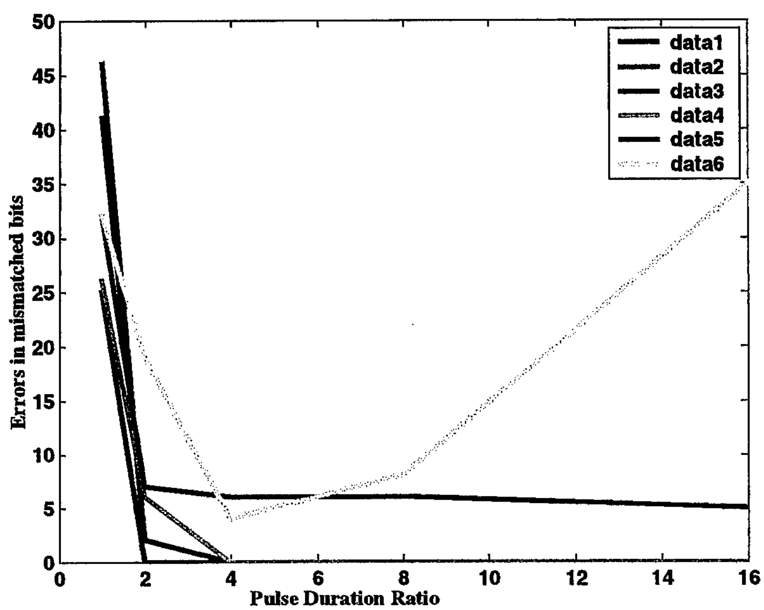

Figure 11. Error vs. pulse duration ratio

For a small a amount of error shown with data1, the system achieves a zero error in mismatched bits for PDR >= 2 which says that, for example, if the modulators are driven at 1 Gigahertz then for perfect performance, at least within the constraints of this model, the laser pulse widths must be equivalent to 2 Gigahertz sinusoids or larger. It is obvious that as θsigma gets larger, the laser pulse widths must be smaller still for error free performance. Any θsigma larger than that given in data5 will never achieve zero error. It is unclear if the plot for data5

ever converges to zero but for all practical considerations and physical implementations, we can eliminate this possibility.

Recall that the vertical polarizer, which basically established the match/mismatch, was selected to have a maximum transmission at 90^0. The value of θmean was selected to prevent the random generation of angles greater than 90^0. It was discovered that if a polarizer is selected with a maximum transmission angle that was equal to θmean there would be some improvement in the error rate. This was done for several values of θmean and it showed that the performance was mainly dependent on θsigma and not on θmean. Using a different value of the maximum transmission of the polarizer than the value of θmean produced poorer results.

Chapter 4: Conclusions and recommendations

Present free space optical techniques rely heavily on Spatial Light Modulators (SLM). If one uses a 1Kx1K SLM clocked at 2.5 KHz., a processing data rate of about 2.5×10^9 bits/sec may be achieved. Presently available off-the-shelf single comparand electronic CAM with 64 bit comparand by 4K memory can process data at about 6.4×10^9 bits/sec.

We can make the following comparison with a device using the MW-OCAPP paradigm. Suppose we propose a device as shown in the analysis, 8 CA words, 8 RA words each with 8 bits per word and use an EO modulator for the RA and CA with clock rates at 1×10^9 Hz. This would give a performance of 5.12×10^{11} bits/sec – about a factor of 100 better than the techniques using SLM and electronic CAM. However, in order to maintain a satisfactory bit mismatch error rate, the laser array would have to consist of pulses whose pulse durations are sufficiently greater than 1 Gigahertz sine pulses. As was shown in the analysis using this simple and much idealized model, this puts a great restriction on RA to provide polarization rotation with sufficiently small variance without using smaller duration laser pulses. Also, this model assumed that the polarization of the laser sources had no variance. In a real application this is not true and the variance of the laser polarizations would just add to the variance of the RA EO modulator to compound the problem.

In conclusion, one must also add other factors such as signal strength required at the detectors to get sufficient S/N for adequate detection. We must also take into consideration the losses incurred from input to output and the necessary requirements of laser power required to maintain an adequate S/N and the synchronization between the CA and RA. One might be able to demonstrate this using large-scale optics but whether or not this would scale well down to smaller devices is not immediately obvious with the present state-of-the-art. If optical approaches to this problem are to be able to compete with the electronics industry, perhaps the approach further proposed by Choo and Louri[5] will offer a practical and realizable solution. This approach uses polarization-insensitive processing by replacing the polarization dependent EO modulators with Mach-Zender interferometers and uses dual-rail logic, i.e., one bit is represented by two pixels. The key here is the fabrication of small relatively cheap Mach-Zender interferometers presently under research for applications in the telecom industry.

Recommendations:

The temporal performance characteristics of the proposed EP^3IC place a great deal of demand on the performance of constituent subsystems. In particular, the polarization modulators must exhibit temporal responses that are much higher than present technology can bear in order

to provide the bit error rates required for precision in performing match/mismatch decisions. Also, the original EP^3IC integrated optical chip proposed assumed an input multiwavelength 32x32 laser array which must be operated in pulse modes exceeding pulse widths in on the order of 10^{-10} seconds and greater to even compete with present technology and achieve the original goal of 82 Tbits/sec throughput. No such large arrays with these performance characteristics are available at this time.

In light of the above, it is recommended that this approach not be considered for further development until the subsystems (mainly the lasers and polarization modulators) have reached a level of development to make the original goal of 82 Tbits/sec feasible.

Acknowledgements: I would like to express my appreciation to Major John Keller, Ph.D. (AFRL/IFED) for his ever present advice in the use of Matlab software and debugging and in acting as a sounding board for some of the procedures used in developing the model. I would also like to acknowledge Dr. Andrew Noga (AFRL/IFEC) for his consultation on use of Matlab software and Richard Floyd (ACS Defense, Inc) for his assistance in debugging the Matlab software model.

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Appendix 1

```
%ScriptModel1_1T

%THIS RUN USES A THETAMU OF 86.4 DEG AND THETASIGMA OF 0.25 DEG. FOR BOTH CA AND RA.
%LINEAR POLARIZER (Filtdeg) AT 86.4 DEG. Change thresholds on Pw0 to .2000, Pw1 to 0.1500 and
% Pw2, Pw4, and Pw8 to .1000 in Detector_Current_Output_t.m

tic;
for loop=1:5

%Establish parameters to define power output from each laser using a nx2 matrix

   %Pmax = 1.2;              %Max power out in watts
   %Pmin = 1.0;              %Min power out in watts
   %pr = 10;                 %Number of lasers (no. rows in vector)
   %pc = 1;                  %Establishes a 2-D Power Vector (no. of columns always equals 1)
                             %Use P = Laser_Power_Array_t(Pmax,Pmin,pr,pc)for function;


   AvgP=1;                   %Establishes the total pulse power for each illuminated bit
if loop==1
   Laser_pulse_width =0;
end                          %0=.5x10^9; 1=1x10^9; 2=2x10^9; 4=4x10^9; 8=8x10^9. These are
                                 sinewave pulses

if loop==2
   Laser_pulse_width =1;         %derived from sinusoids of these respective frequencies.
end
if loop==3
   Laser_pulse_width =2;
end
if loop==4
   Laser_pulse_width =4;
end
if loop==5
   Laser_pulse_width =8;
end

%Establish parameters to define wavelength of each laser illuminating each row of CA

   Wmax = 1.6;               %Max wavelength in micrometers assuming flat distribution
   Wmin = 1.1;               %Min wavelenght in micrometers assuming flat distribution
   wr =  10;                 %No. of lasers (no. of rows in vector)
   wc = 1;                   %Establishes a 1-D Wavelength Vector (no. of columns always equals 1)

 %Establish pulse widths for CA_Modulator

 CA_pulse_width=0;           %0=.5x10^9; 1=1x10^9; 2=2x10^9; 4=4x10^9; 8=8x10^9. These are sinewave
pulses
                             %derived from sinusoids of these respective frequencies.
 tpulse=[0:10^-12:10^-9];    %time vector
```

%Establish parameters for Generating the output from the CA (Generate_CA_t_Output)

```
CAin_jones_vector=[1;0];          %Initial x-polarized light from lasers
DegMu = 86.4;                     %Angle in Degrees for thetaMu
thetaMu = pi*DegMu/180;           %Average rotation angle of CAin_jones_vector by CA modulator in
radians
DegSigma = 0.40;                  %Standard deviation of angle for thetaSigma in degrees
thetaSigma = pi*DegSigma/180;     %Standard deviation of rotation angle from thetaMu
car= 8;                           %Number of rows in Comparand Array (CA)
cac = 8;                          %Number of columns in Comparand Array (CA)
```

%Establish pulse widths for RA_Modulator

```
RA_pulse_width=0;           %0=.5x10^9; 1=1x10^9; 2=2x10^9; 4=4x10^9; 8=8x10^9. These are sinewave
                            pulses derived from sinusoids of these respective frequencies.
```

%Establish parameters for generating the output from the RA Modulator(Generate_RA_t_Output)

```
DegMuRA = 86.4;                     %Angle in Degrees for thetaMuRA
thetaMuRA = pi*DegMuRA/180;         %Average rotation angle by RA Modulator of input CA_out_t
DegSigmaRA = 0.40;                  %Standard deviation of angle for thetaSigmaRA in degrees
thetaSigmaRA = pi*DegSigmaRA/180;   %Standard deviation of rotation angle from thetaMuRA
rar = 8;                            %Number of rows in Relational Array (RA)
cac = 8;                            %Number of columns in Relational Array (RA) which is same as CA
                                    columns
```

%Establish parameters for Polarization Filter #2 to pass only vertically polarized (y) light.

```
FiltDeg = 86.4;               %Angle in degrees for theta_P2
theta_P2=pi*FiltDeg/180;      %Angle for which vertically polarized light has maximum transmission
```

%Establish parameters for DEMUX_Light for color of light

%All variables and parameters have been established in previous M-file computations

%Establish Grating parameters to split light up into colors using Grating_t

```
grating_eff_t = .1;       %Grating efficiency is assumed constant throughout all gratings and wavelengths
```

%Establish parameters for detector current output

```
%threshold = .05;         %Theshold on NormSumIout_t separating "0" and "1". Provides threshold value
                          %for DetectNormSumIout_t binary output.
```

%Perform functional computations based on above input parameters

```
[Single_Pulse_0,Pulse_Range_0] = Pulse_Generator_0(tpulse);
[Single_Pulse_1,Pulse_Range_1] = Pulse_Generator_1(tpulse);
[Single_Pulse_2,Pulse_Range_2] = Pulse_Generator_2(tpulse);
[Single_Pulse_4,Pulse_Range_4] = Pulse_Generator_4(tpulse);
[Single_Pulse_8,Pulse_Range_8] = Pulse_Generator_8(tpulse);
W=Laser_Wavelength_Array_t(Wmax,Wmin,wr,wc);
CA_t =
CA_Modulator_t(tpulse,CA_pulse_width,Single_Pulse_0,Single_Pulse_1,Single_Pulse_2,Single_Pulse_4,Single_P
ulse_8);
```

```
[CAout_t,CAbinary_t,CAthetamax] =
Generate_CA_t_Output(tpulse,CA_t,CAin_jones_vector,thetaMu,thetaSigma,car,cac);

P_t=Pulsed_Laser_t(AvgP,tpulse,Laser_pulse_width,Single_Pulse_0,Single_Pulse_1,Single_Pulse_2,
Single_Pulse_4,Single_Pulse_8);

RA_t=RA_Modulator_t(tpulse,RA_pulse_width,Single_Pulse_0,Single_Pulse_1,Single_Pulse_2,Single_Pulse_4,
Single_Pulse_8);

[RAout_t,RAbinary_t,RAthetamax]=Generate_RA_t_Output(CAbinary_t,RA_t,CAout_t,thetaMuRA,thetaSigmaRA
,car,rar,cac);

P2out_t = Polarization_Filter2_t(theta_P2,RAout_t,car,rar,cac);

[DEMUX_t, NORMA_t] = DEMUX_Light_t(P2out_t,car,rar,cac);

clear RAout_t;

clear P2out_t;
[Grating_Inputs_t,Grating_Outputs_t] = Grating_t(P_t,NORMA_t,grating_eff_t,car,rar);

[PR,Iout_t,ActualSumIout_t,SumIout_t,DetectSumIout_t] =

Detector_Current_Output_t(Laser_pulse_width,W,Grating_Outputs_t,car,rar);

clear Iout_t;

H_t = matchtest_t(CAbinary_t,RAbinary_t,car,rar,cac);

Demux_t = Demux_Matrix_t(H_t);

[Total_BER,Bit_error_rate,Word_error_rate] = Bit_Error_Rate(Demux_t,DetectSumIout_t,car,rar);

% The following code is used to completely run the total script and store results from previous runs without human
% intervention. The script is usually run for all 5 laser pulse widths (0,1,2,4,8) without intervention. It takes about
%5 hours of run time.

if loop==1
   SumIout_t_0=SumIout_t;
   DetectSumIout_t_0=DetectSumIout_t;
   ActualSumIout_t_0=ActualSumIout_t;
   Demux_t_0=Demux_t;
   CAbinary_t_0=CAbinary_t;
   RAbinary_t_0=RAbinary_t;
   Bit_error_rate_0=Bit_error_rate;
   Total_BER_0=Total_BER;
   Word_error_rate_0=Word_error_rate;
   CAthetamax_0=CAthetamax;
   RAthetamax_0=RAthetamax;
end
if loop==2
   SumIout_t_1=SumIout_t;
   DetectSumIout_t_1=DetectSumIout_t;
   ActualSumIout_t_1=ActualSumIout_t;
   Demux_t_1=Demux_t;
   CAbinary_t_1=CAbinary_t;
```

```
  RAbinary_t_1=RAbinary_t;
  Bit_error_rate_1=Bit_error_rate;
  Total_BER_1=Total_BER;
  Word_error_rate_1=Word_error_rate;
  CAthetamax_1=CAthetamax;
  RAthetamax_1=RAthetamax;
end
if loop==3
  SumIout_t_2=SumIout_t;
  DetectSumIout_t_2=DetectSumIout_t;
  ActualSumIout_t_2=ActualSumIout_t;
  Demux_t_2=Demux_t;
  CAbinary_t_2=CAbinary_t;
  RAbinary_t_2=RAbinary_t;
  Bit_error_rate_2=Bit_error_rate;
  Total_BER_2=Total_BER;
  Word_error_rate_2=Word_error_rate;
  CAthetamax_2=CAthetamax;
  RAthetamax_2=RAthetamax;
end
if loop==4
  SumIout_t_4=SumIout_t;
  DetectSumIout_t_4=DetectSumIout_t;
  ActualSumIout_t_4=ActualSumIout_t;
  Demux_t_4=Demux_t;
  CAbinary_t_4=CAbinary_t;
  RAbinary_t_4=RAbinary_t;
  Bit_error_rate_4=Bit_error_rate;
  Total_BER_4=Total_BER;
  Word_error_rate_4=Word_error_rate;
  CAthetamax_4=CAthetamax;
  RAthetamax_4=RAthetamax;
end
if loop==5
  SumIout_t_8=SumIout_t;
  DetectSumIout_t_8=DetectSumIout_t;
  ActualSumIout_t_8=ActualSumIout_t;
  Demux_t_8=Demux_t;
  CAbinary_t_8=CAbinary_t;
  RAbinary_t_8=RAbinary_t;
  Bit_error_rate_8=Bit_error_rate;
  Total_BER_8=Total_BER;
  Word_error_rate_8=Word_error_rate;
  CAthetamax_8=CAthetamax;
  RAthetamax_8=RAthetamax;
end
end
clear H_t;
clear NORMA_t;
toc
```

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